HOME

SPECS

The Kilometer-baseline Far-IR Interferometer in NASA's Space Science Roadmap

Dave Leisawitz[a]
Infrared Astrophysics Branch
NASA GSFC

Tom Abel[b], Ron Allen[c], Dominic Benford[a], Andrew Blain[d], Claudio Bombardelli[e], Daniela Calzetti[c], Michael J. DiPirro[a], Pascale Ehrenfreund[f], Neal Evans[g], Jackie Fischer[h], Martin Harwit[i], Tristram T. Hyde[a], Marc J. Kuchner[j], Jesse Leitner[a], Enrico Lorenzini[e], John C. Mather[a], Karl Menten[k], S. Harvey Moseley[a], Lee G. Mundy[l], Takao Nakagawa[m], David Neufeld[n], John C. Pearson[o], Stephen A. Rinehart[a,p], Juan Roman[a], Shobita Satyapal[q], Robert F. Silverberg[a], H. Philip Stahl[lr], Mark Swain[o], Theodore D. Swanson[a], Wes Traub[e], Edward L. Wright[s], and Harold W. Yorke[o]

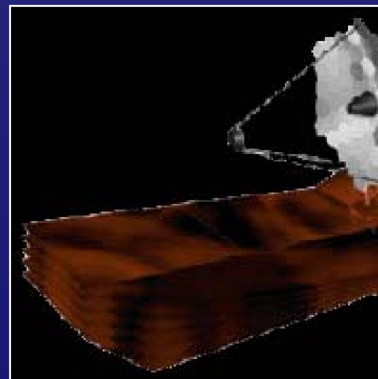
a - NASA GSFC
b - Penn State Univ.
c - STScI
d - Caltech
e - CfA
f - Leiden Univ.
g - UT Austin
h - NRL
i - Cornell
j - Princeton Univ. k -MPIfR
l - Univ. Maryland
m - ISAS/JAXA
n - Johns Hopkins Univ.
o - NASA JPL/Caltech
p - NRC Research Associate
q -George Mason Univ.
r - NASA MSFC
s - UCLA

Industrial Partners:
Ball Aerospace, Boeing, Lockheed Martin, Northrop Grumman

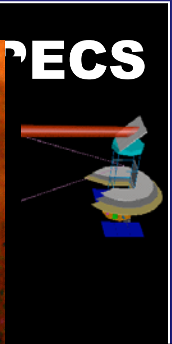
Outline

- Context: community planning and study status
- Science goals
- Mission requirements
- Mission concepts for SPIRIT and SPECS
- Tethered formation flying, a key enabling technology

The Path Leading to SPECS

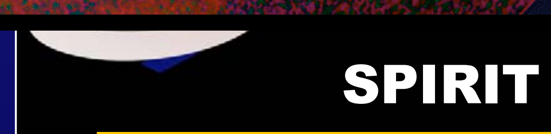


Single Aperture Telescope



ter Probe of
on of Cosmic

2020



Space Infrared Interferometric Telescope

2010

SPICA

Herschel

SOFIA

Spitzer

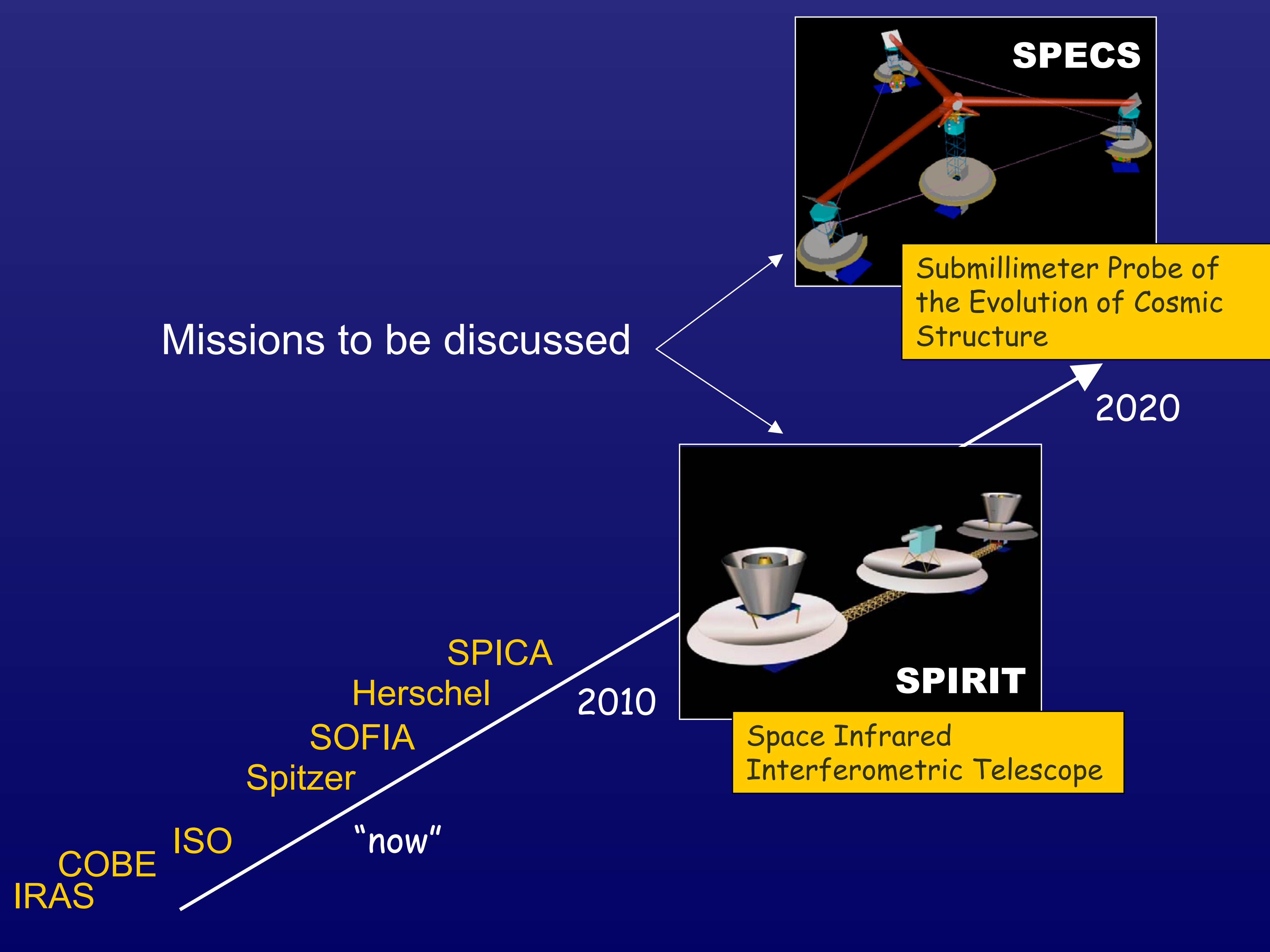
ISO

COBE

IRAS

"now"

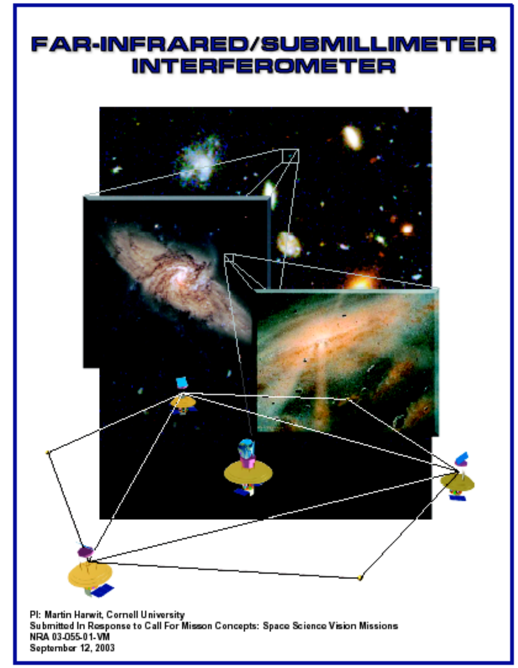
In Europe, two white papers submitted for *Cosmic Vision* planning also call for far-infrared/submillimeter space interferometry


Missions to be discussed
SPECS
Submillimeter Probe of the Evolution of Cosmic Structure
2020
SPIRIT
Space Infrared Interferometric Telescope
2010
SPICA
Herschel
SOFIA
Spitzer
ISO
COBE
IRAS
"now"

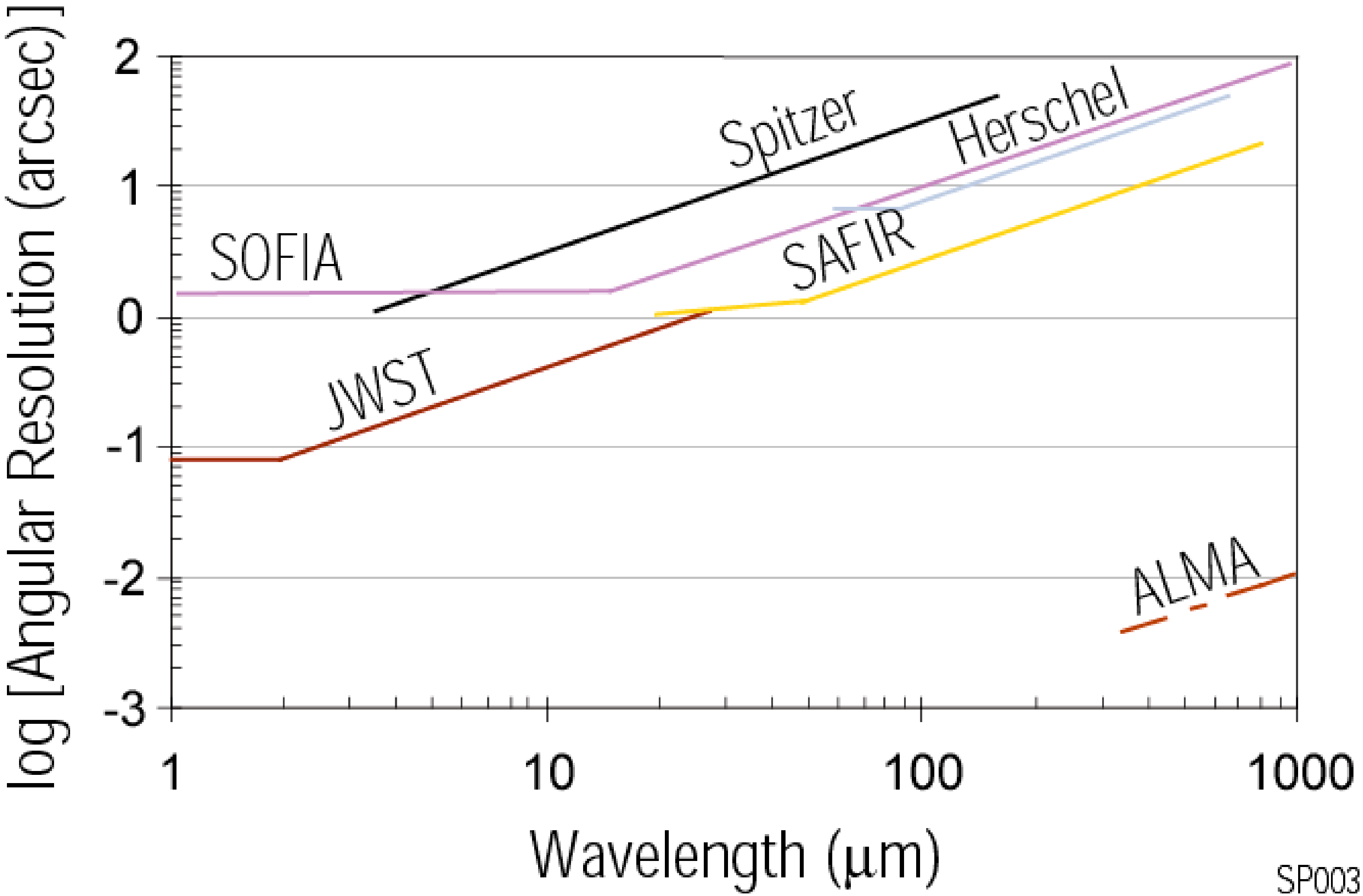
Mission Study Status

- The Infrared Era has begun
  - Spitzer now
  - Herschel soon
  - international community and public interest
  - new information from Spitzer available for mission planning

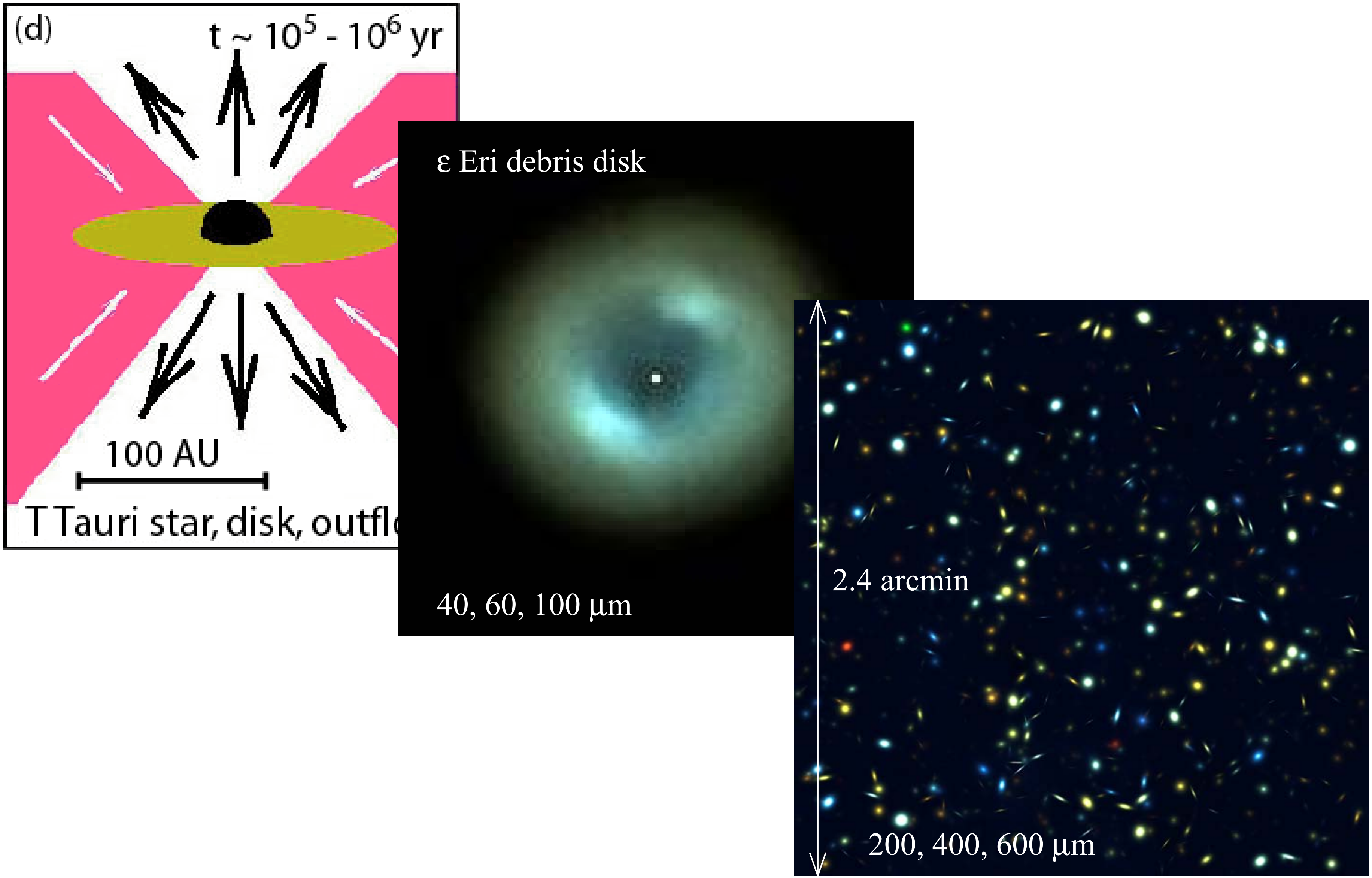
- Key elements of the *Community Plan* are being implemented
  - SAFIR and **SPECS** Vision Mission studies underway
  - **SPIRIT** “Origins Probe” study underway
  - Opportunities to report to NASA’s Astronomy and Physics Roadmap Committees coming in December and January
  - Reasonable progress on all technology frontiers



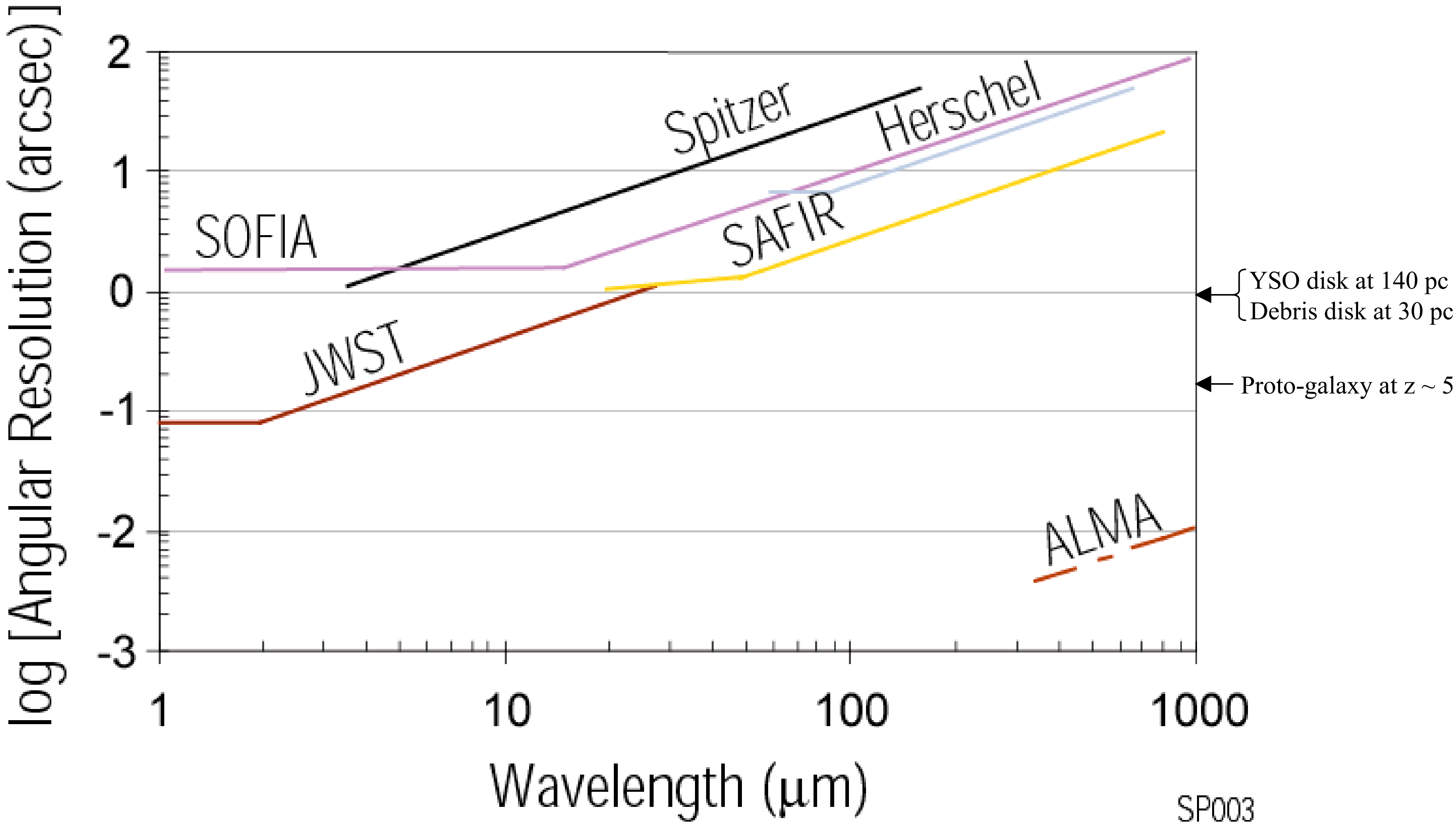
The Importance of High Angular Resolution



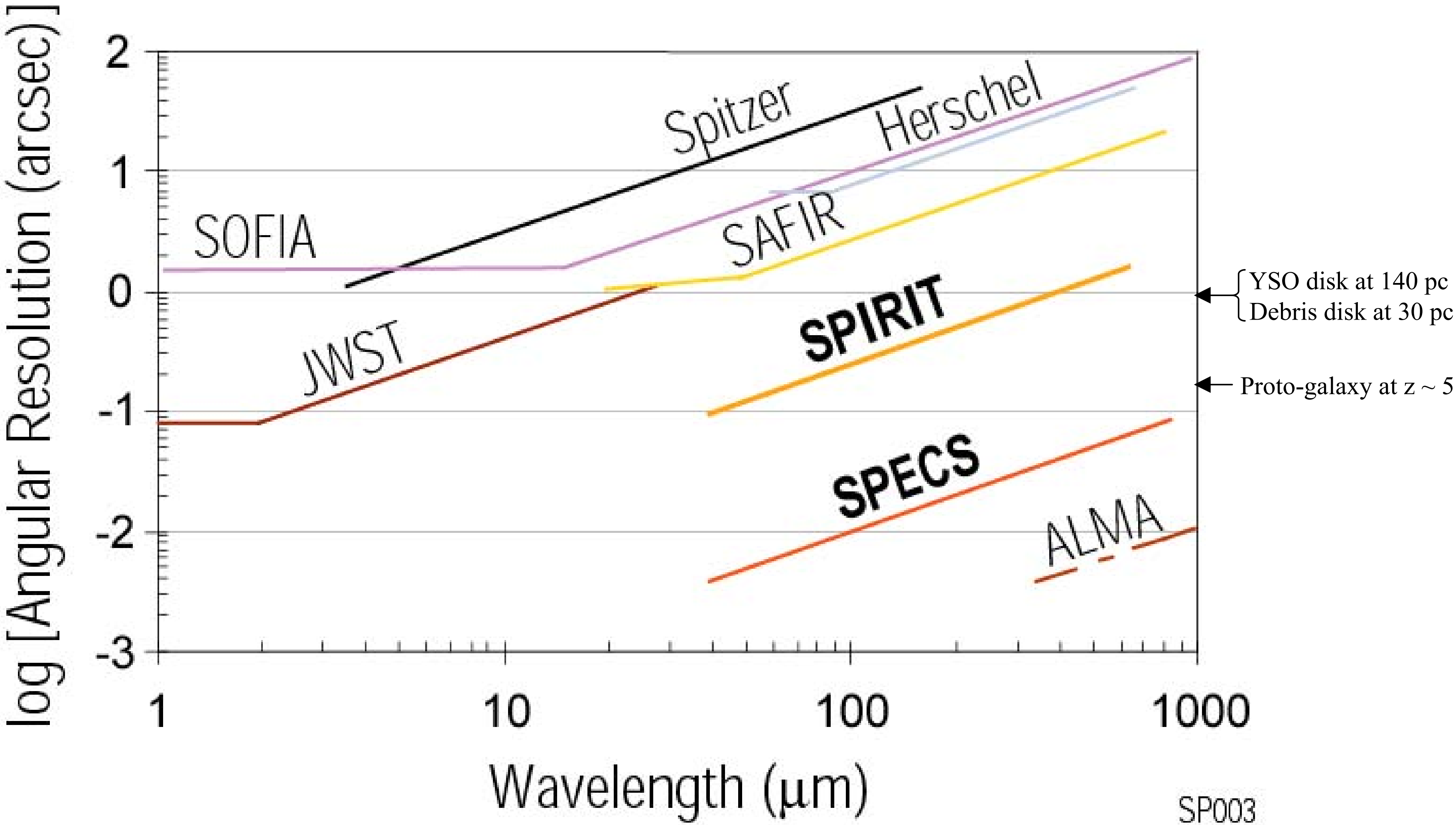
The Importance of High Angular Resolution



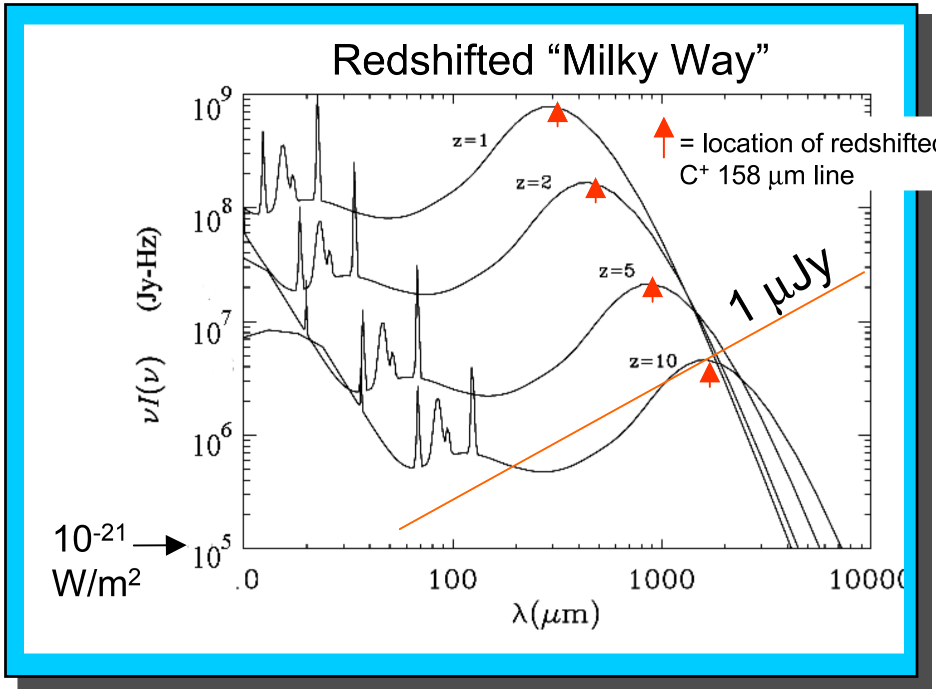
The Importance of High Angular Resolution

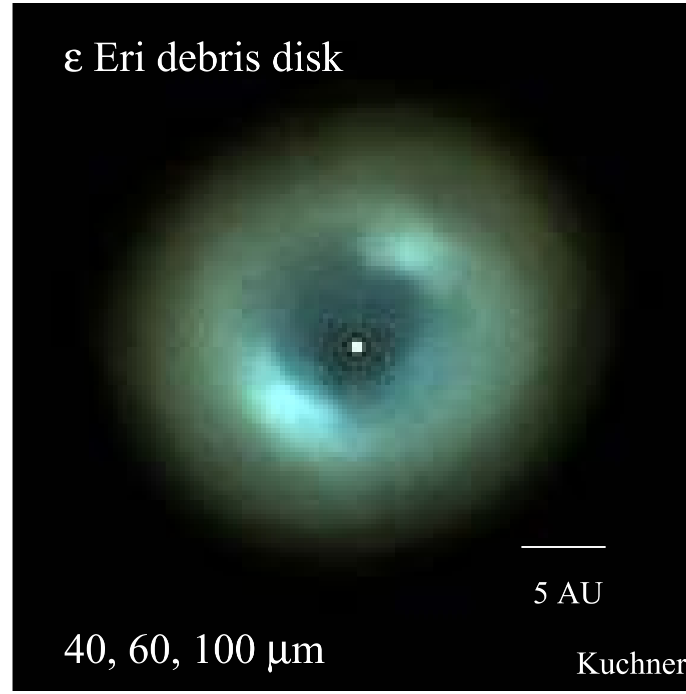


The Importance of High Angular Resolution



Sensitivity Requirements: Distant and Local





To see an L* galaxy at high z, need better than 1 µJy sensitivity. Protogalaxies might have been ~100x fainter.

To image debris disk dust emission on a 1 AU scale, need ~1 µJy sensitivity.

Why Interferometry?

An interferometer is a good design choice when angular resolution rather than sensitivity drives the aperture size requirement

Spatial resolution:

$\Delta\theta = 10$ mas $(\lambda / 100\ \mu m)(b_{max} / 1\ km)^{-1}$

for maximum baseline b_{max} at wavelength λ. (For comparison, a diffraction limited 10 m telescope provides 2.5 arcsec resolution at 100 μm.)

Spectral line sensitivity for an unresolved (point) source:

MDLF ~ 7×10^{-22} W/m^2 $\{FBW\ I_{\nu,\ bg}(MJy/sr)/[n(n-1)(\tau_{sys}/0.1)]\}^{1/2}(D/4m)^{-2}(t/10^5 s)^{-1/2}$

for n = 3 mirrors of diameter D in integration time t, where τ_{sys} is the system efficiency and FBW, the fractional bandwidth, could be ~0.7.

In the far-IR/sub-mm, a total light collecting area comparable to that of JWST provides ample sensitivity, but an effective aperture diameter (b_{max}) of ~30 - 50 m is needed to overcome extragalactic source confusion into the sub-mm, 1 km to provide HST (or JWST) class angular resolution.

Far-IR Diagnostic Potential

Spectroscopy is vital to our ability to answer the important science questions.

For extragalactic problems we might be satisfied to measure the integrated line intensity. R ~ 1000 would be okay.

However, for star formation research we are interested in resolving lines. For this we desire R > 10^5.

Typical Spectral Lines[1]	Derived Properties
Starburst Galaxies	
[ArIII]**9**/[ArII]**7**,[NeIII]**15**/[NeII]**12**, [NIII]**57**, [NII]**122**	Ionizing SED[2], U[3], IMF[4], age
H recombination lines	Age, IMF, starburst luminosity
Dust features	Starburst luminosity
Active Galactic Nuclei (AGN)	
[NeV]**14**,**24**/[NeIII]**15**, [OIV]**25**, [SiIX]**4**	U, SED
Broad H recombination lines	Buried AGN
Dust features	AGN luminosity
Interstellar Medium (ISM)	
HII Regions	
[NeIII]**36**/[NeIII]**15**, [SIII]**34**/[SIII]**19**, [OIII]**52**/[OIII]**88**	Visual extinction (A_V), electron density (n_e)
All Ne lines, H recombination	Abundance
AGN Narrow Line Region (NLR)	
[NeV]**14**/**24**, [NeIII]**36**/**15**	A_V(NLR), n_e
Photon Dominated Regions, Shocks	
H_2 **2**, [S I]**25**, [SiII]**35**, PAH[6] features, [CII]**158**, [OI] **63**,**145**, [FeII]**18**,**24**,[FeIII]**24**	Far-UV field strength & SED, density, temperature, shock parameters
Molecular Clouds, Protostars, and Disks	
Rotational and rovibrational lines of H_2O, CO, and small hydrides	Temperature, density, turbulent & systemic velocities, isotopic abundances

[1] Rest wavelengths in µm, but redshifted at high z
[2] Spectral Energy Distribution
[3] Ionization parameter
[4] Initial Mass Function

“Flow Down” from Science Questions to Technology Requirements: SPECS

SPECS Requirements Flow Down

Science Goals

- Characterize the epoch of first generation star formation
- Probe the luminosity evolution and physical conditions in galaxies since the epoch at which they formed
- Observe the chemical and dynamical processes that lead to the formation of stars
- Image the dusty disks around newly formed stars to study temperature, density, grain size distribution and chemical fractionation to learn how planetary systems form

Measurement Capabilities

Far-IR and Submillimeter Imaging and Spectroscopy

Spectral Range
40 - 600 μm required
30 - 800 μm desirable

Angular Resolution
0.05 (λ / 250 μm) arcsec

Spectral Resolution
$\lambda/\Delta\lambda = 1000$ for galaxies and 10^5 for protostars

Field of View
1’ required, >1.5’ desired

Sensitivity
1 μJy for continuum and 10^{-22} W m^{-2} for spectral lines in 10^5 sec

Dynamic Range
10^3 - 10^4

Observations
At least one target a day

Engineering Implications

- 2 or 3 light collectors plus Michelson beam combiner and spectrometer
- 3 - 10 m diameter collector mirrors
- 4 K optics
- 0.5 μm mirror surface
- Metrology to ~1 μm
- sub-arcsecond relative pointing

• Detectors
- NEP < 10^{-20} W Hz$^{-1/2}$
- 50 x 50 pixel array

• Orientation
- Able to view at least +/-20° from ecliptic

Key Technologies

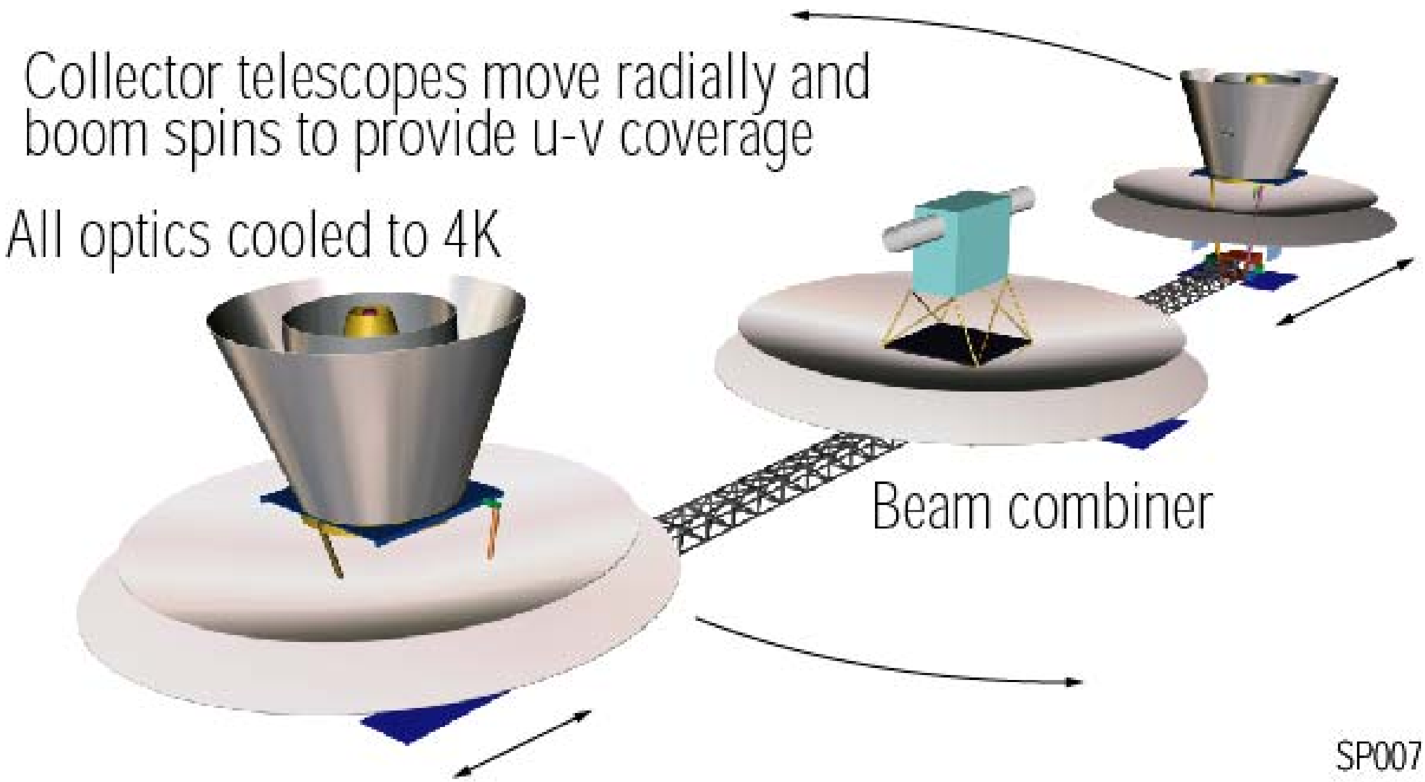
Active and passive cooling
- 0.1 K coolers
- Mechanical coolers
- 4K cooling loops
- Deployable multi-layer sunshields

Formation flying
- Tethers in spin-stabilized formation
- Inertial referencing for phasing, guiding

Optics and interferometry
- Lightweight 4K optics (3 - 10 m)
- Wide-field imaging interferometry
- Cryogenic delay line

From analysis of the science team’s Design Reference Mission (“use cases”)

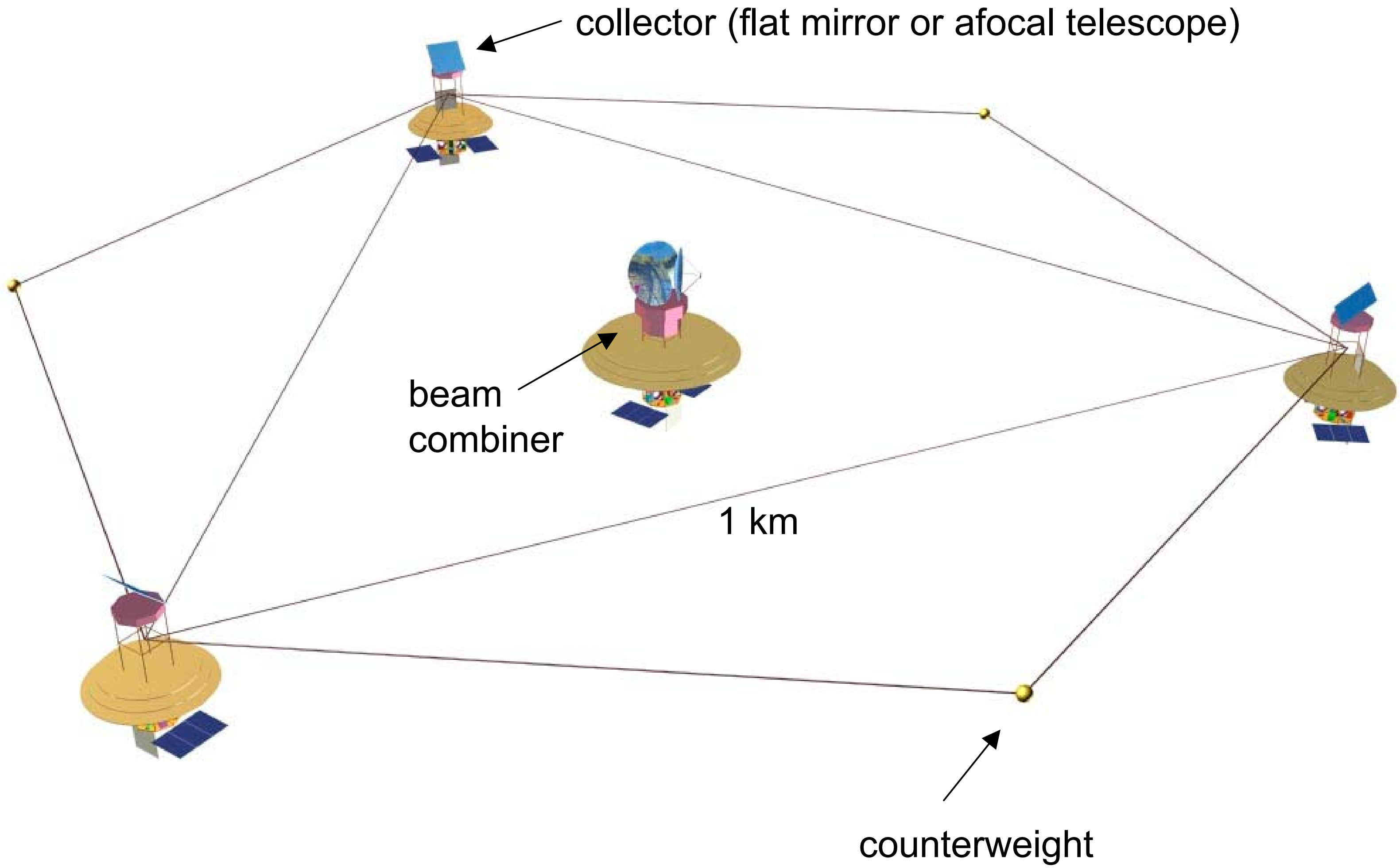
SPIRIT Mission Concept



SPIRIT could fly in the next decade as an Origins Probe

SPECS Mission Concept

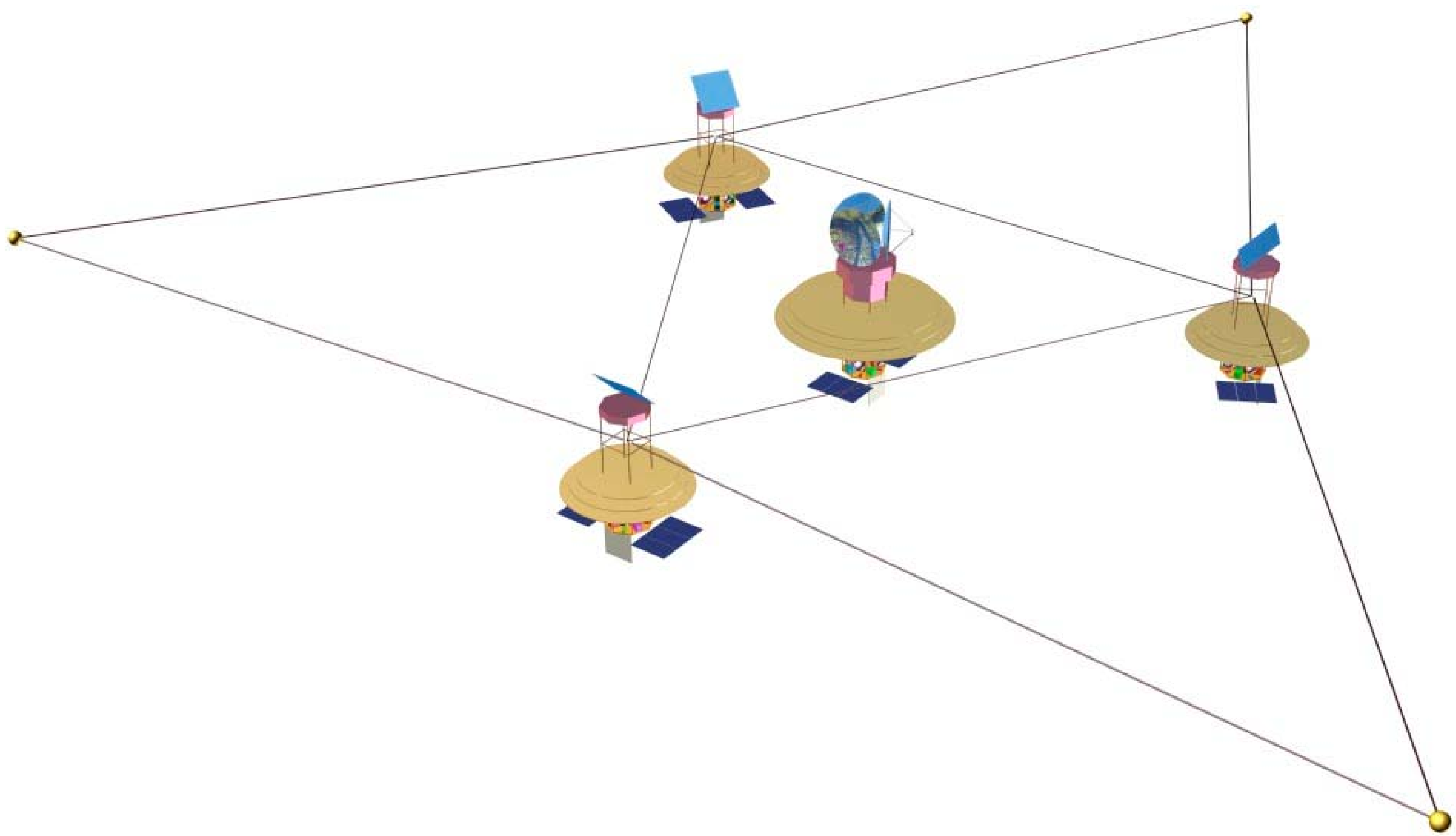
Fully extended array



Tether configuration developed by Farley and Quinn (2001)

SPECS Mission Concept

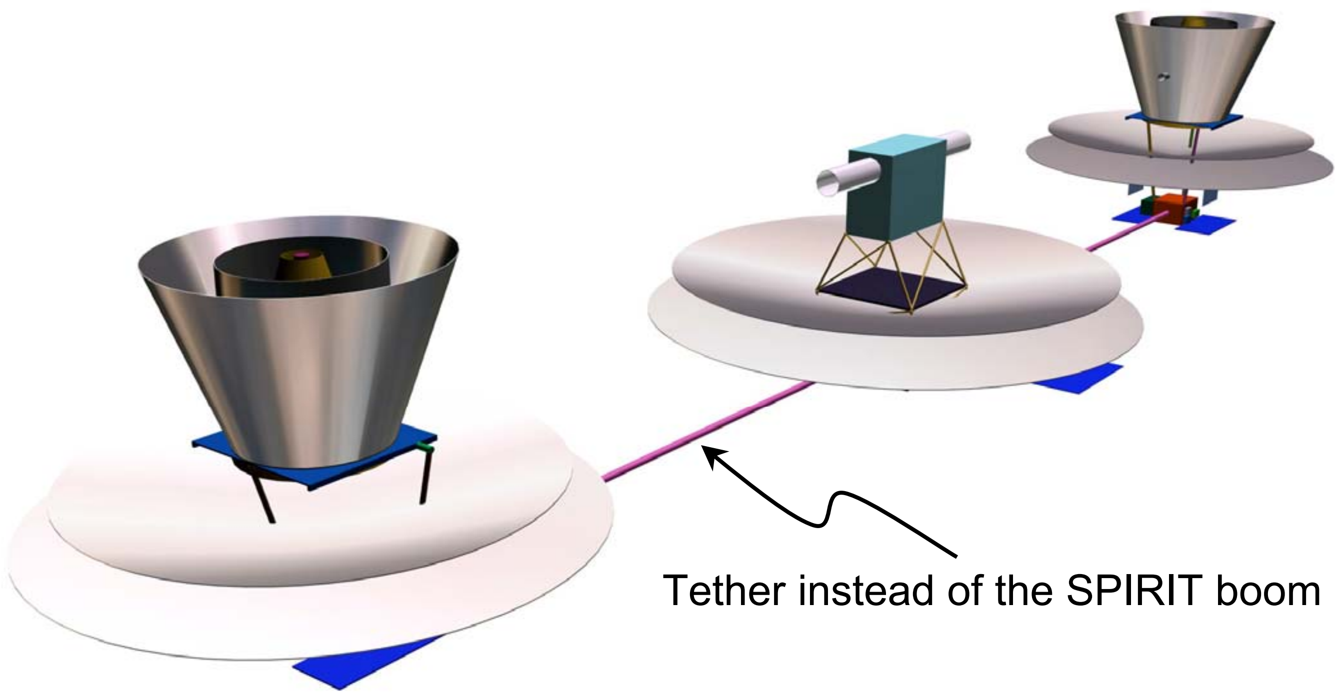
Partially contracted array



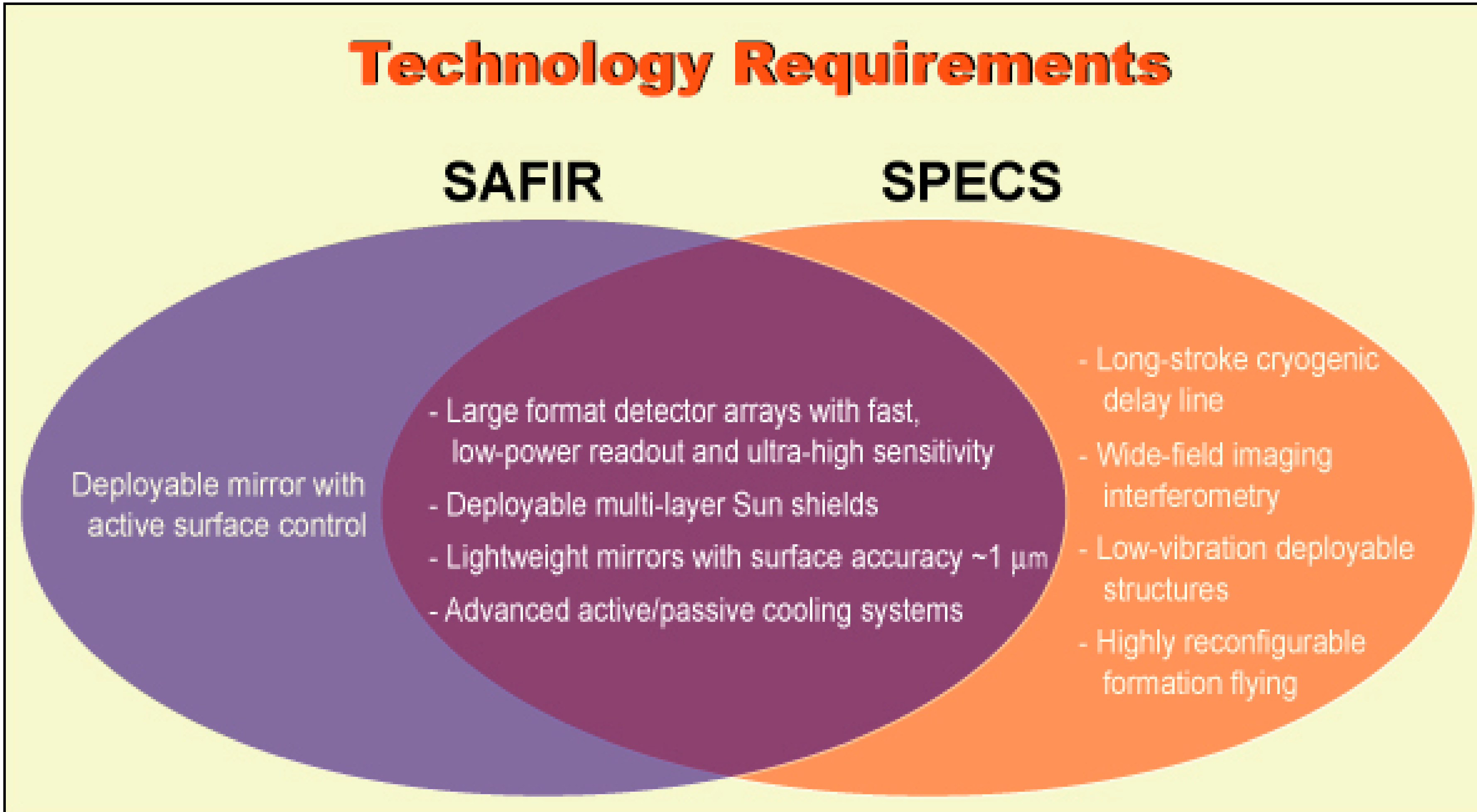
2-collector systems and off-axis afocal telescopes are under study

SPECS Simple Concept

Linear array



Technology: Heritage and Common Needs



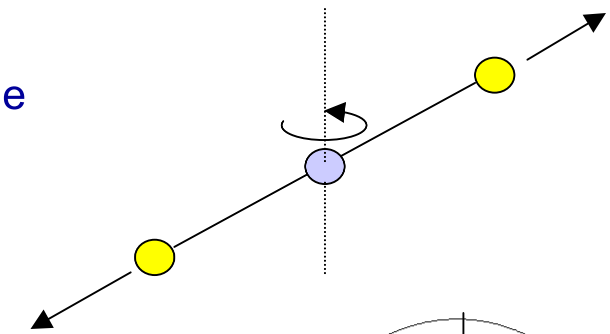
- Stable boom and metrology in common with SIM
- Wide-field double Fourier technique in common with TPF-I/Darwin

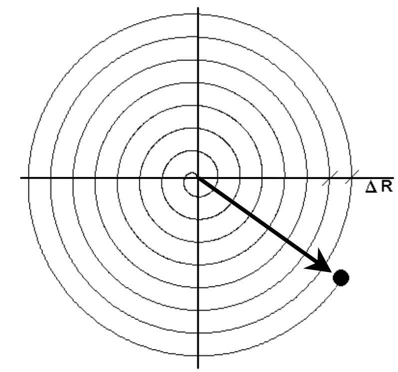
Highly Reconfigurable Arrays

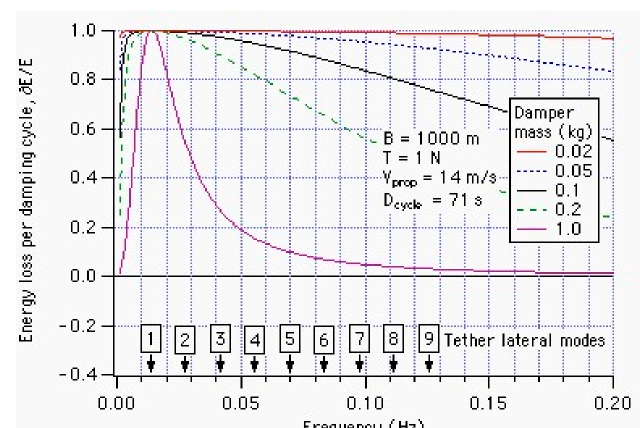
- "Highly reconfigurable" for dense *u-v* plane coverage
- Rotating deployable boom with light collectors on trolleys - works for b_{max} up to ~50 m
- Formation flying works for b_{max} up to ~200 m (too much thruster propellant or too few images per mission if b_{max} bigger)
- Formation flying <u>with tethers</u> works for b_{max} up to ~1 km
  - Quinn et al. study suggests viability, addresses requirements, alternative architectures, re-pointing; tools developed to facilitate further analysis
  - Lorenzini et al. have analyzed tether dynamics
  - Sell et al. adapting SPHEREs to test tethers, could lead to air table demo and first space demo
  - Need inexpensive long-baseline space demo scalable to SPECS

Formation Flying with Tethers

- Propellant mass prohibitively large for a highly-reconfigurable, km-baseline array (essential for good image quality)
- Tethers have many advantages:
  - light weight
  - passive stability
  - ease of reconfiguration
  - easier metrology and spacecraft relative bearing
  - planar spin-stabilized tethered configuration can have many shapes
- Centrifugal forces in the spin plane provide tether tension and shape stability
- High angular momentum due to spin provides stable pointing to target and low sensitivity to external torques
- For heliocentric and L2 halo orbits cm-level stability of tethered units is provided by spin-stability with no need for thruster control during station-keeping
- Tether oscillations, excited by maneuvers, can be damped out in minutes (long baselines) or seconds (short baselines)
- With damping, tethered formation naturally converges to rigid flat spin configuration
- Tether noise spectrum is at low frequency (periods from a fraction of a second to a minute)







Summary

- SPIRIT and SPECS satisfy critical needs of NASA's space science program (e.g., characterize exo-zodi debris disks) and address compelling scientific questions (How did we wind up on a watery rock orbiting the Sun in the disk of a spiral galaxy?)
- Broad support exists for far-IR/sub-mm space interferometry in the international scientific community
- SPIRIT could fly next decade as an "Origins Probe" (SPECS will come later)
- **Formation flying with tethers is an enabling technology for space-based long-baseline imaging interferometry**